

PLATE 16.

Fig. 9.—Mount Elgon Initiation Rites. Before the initiation ceremony the young men perform dances at various villages and receive gifts for the circumcision feast. On the day of the ceremony, before the event takes place, they go round the village and drive out hostile ghosts supposed to be lurking round.

Fig. 10.—Mount Elgon. During the operation of circumcision the patient stands with arms extended upwards, and must show no sign of timidity. Should he either utter a sound of pain or move a muscle he is branded a coward. Shame will force such a youth to commit suicide rather than face his companions afterwards.

A Quantum Theory of Colour Vision.

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In a paper on the subject of the Quantum Theory of Vision, issued in the 'Philosophical Magazine' (February, 1921), I dwelt on the view that the sensation of light is in every case stimulated by the action of photo-electrons set free in the retina. Further, the energy of the photo-electron being proportional to the frequency of the light, the strength of the stimulus produced is the all-sufficient origin of colour sensations. That *colour* is entirely a cerebral phenomenon is evident. Light, visible and invisible, consists of a uniformly graduated series of wave motions or energies. There is nothing to distinguish one part of the spectrum from another save the difference of wave-length or frequency. But objects in Nature react differently towards these waves: absorbing some, reflecting others, and so the selective effect of natural objects towards light has discovered to the organism a means of improving on mono-chromatic vision: a means of distinguishing objects by their selective absorption and reflection. Our colour sensations were developed solely for this purpose and solely under the influence of the light reflected by natural objects. Hence, a limited number of fundamental sensations being the simplest, if not indeed the only, way of securing the desired end, we would expect that these sensations would be developed so as most effectively to interpret the frequencies met with among natural objects reflecting solar light. The evolutionary development of three highly developed colour sensations according to the extreme and mean regions of the spectrum is the result. Colour sensations, *i.e.* (white), red, green, and blue were evolved, whereby the whole gamut of the spectrum can be dealt with.

In my former paper I restricted my reference to colour vision to this evolutionary aspect of the matter. In the present paper I have something to add respecting the retinal apparatus developed to subserve the end which Nature had in view.

(1) The law defining the stimulation of excitable tissues known as the "All or none" law is generally accepted by physiologists. It comes to this: in order that a disturbance be set up and propagated in a nerve, the exciting cause must possess a certain minimal intensity. The intensity of the transmitted effect is a constant proper to the particular tissue. When end effects—*e.g.*, muscular contraction—exhibit different grades of intensity, this is due to difference in the numbers of fibres activated by the primary stimulus. If one fibre only existed in the nerve, one intensity only of end effect is possible, whatever be the intensity of the exciting stimulus. There may be a summation of stimuli. A stimulus too weak to activate the nerve leaves behind it a local change at the point of application. A second stimulus arriving before the condition induced by the first stimulus has passed away may produce the effect of the minimal stimulus.

The existence of a "refractory period" must also be noted. This appears to be a period of recuperation during which the nerve fibre regains its excitability. "All excitable tissues are incapable of response to a second stimulus applied at a short interval of time, differing in different tissues, after a previous one."* In the latter part of the refractory period stimuli stronger than normal may secure excitation, but the magnitude of the disturbance propagated is subnormal. The refractory state appears to act as inhibiting the transmission of a too sustained and intense disturbance; the recuperative influence at the nerve terminal being, as it were, used up as fast as it is generated.

The refractory interval must vary greatly according to the nature of the tissue. It may be as great as 0.002 sec. when nerves controlling muscular excitation are concerned. Stimuli travelling over nerves concerned with audition must succeed each other many thousands of times in a second in order that note-frequency be interpreted to the brain. Thus the researches of Wrightson and Keith point to four impulses per wave being necessary. Middle C would, therefore, require over 1,000 impulses per second, and a note of 15,000 vibrations per second (higher and audible) would require 60,000 impulses per second.†

(2) The bearing of these laws on the present subject is obvious. If the

* Bayliss, 'General Physiology,' p. 433.

† Keith in Sir Thomas Wrightson's 'The Analytical Mechanism of the Middle Ear,' 1918, p. 212.

varying energies of the photo-electrons are to be transmitted to the cerebral cortex, and if such energy differences cannot be conveyed by the nerve fibre, the alternatives presented to us are either to reject the theory altogether or to assume that more than one nerve fibre transmit the stimuli concerned with colour vision, and that it is by the number of fibres stimulated that the energy is interpreted. This naturally sends us to the histology of the retina, because as colour vision appears to be restricted to the cones and achromatic vision to the rods, the connections of these organs with the optic nerve might be expected to reveal an anatomical difference in accordance with the structural features we are driven to assume as existing in the cones.

This anatomical difference is presented to us with remarkable clearness. All delineators of these minute organs agree in depicting the rod as connected through a fibre of extreme tenuity with the deeper lying nervous structures; while on the other hand, the corresponding connection of the cone is, relatively to that of the rod, exceedingly bulky. The accompanying figure (after Greeff) shows these features in a conspicuous manner. Obviously many such fibres as lead from the rod might be contained in the cone fibre. Indeed it is difficult to account for the remarkable difference of structure on any other suggestion.

(3) I assume that the explanation is correct and that the constituent fibres of the cone connection are collected in the spindle-shaped enlargement of the organ and brought to the base of the percipient extremity, where their terminals are activated by energy carried into the cone by photo-electrons. It may be that the fibrils persist into the cone or into the cylindrical percipient extremity of the foveal cone. In either case the number of fibres activated depends on the kinetic energy of the photo-electron.

On this view we find a purely anatomical reason for the differing functions of rods and cones. The photo-electrons liberated within the rod can transmit but the one intensity of stimulus to the brain, no matter how much they may differ in kinetic energy. Hence its achromatic functions and the low luminous character of scotopic vision. A one-fibre stimulus is all it can send. On the other hand the cone sends a number of stimuli proportional to the energy of

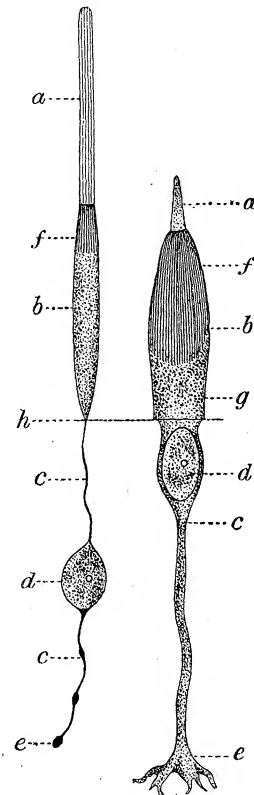


FIG. 1.

the exciting electron; and evokes grades of sensation owing to the possession of more than one fibre connection with the brain.*

(4) It may be objected that the energy of the photo-electron is too small to be divided. The answer is that it is not the energy of the electron which travels to the brain. The "all or none" law and the fact of the refractory period plainly indicate that the stimulus is a trigger action. And where we are dealing with the equilibria of molecular systems of extreme delicacy we are not entitled to limit the possibilities. True we are not in a position to state the character of the operative mechanism. But here, as elsewhere in physiological and physical science, we necessarily leave, and are clearly entitled to leave much to the unknown.

(5) Although the conditions involved appear to be very complex some discussion of the bearing of this view of the structure of the cones on colour vision may be permissible. It is evident that the activation of the nerve fibres in definite numerical groups according to the energy of the photo-electron may be regarded as realising Young's three kinds of nerve fibre or the three "apparatus," which, by various writers have been postulated as accounting for colour vision.

(6) We are presented in the visible spectrum with a series of frequencies ranging over about one octave. The corresponding quanta appear in the photo-electron and must be reckoned with, whatever view we may hold respecting the number of primary colour sensations.

It will, however, conduce to clearness and at the same time, very probably, lead us nearest to the actual facts if we assume three primary colour sensations.

Various spectral positions have been assigned by different authorities to these sensations. The difficulty of the subject is revealed by these differences. Helmholtz bases his selection on curves plotted to represent the rate of change of hue attending change of wave-length. Such curves show two regions of special sensitivity respecting change of hue; one in the yellow and one in the blue-green. These positions of maximum change, although originally derived by direct observations,† mark the intersections of the colour sensation curves and may be referred to parts of the spectrum where the ordinates of the colour curves are most rapidly changing in relative value. Helmholtz's fundamental green sensation is located between these points at $540\text{ }\mu\mu$ to $560\text{ }\mu\mu$. König's green sensation curve attains its maximum

* It seems not improbable that the evolutionary development of the cone originated in the fusion of the rods to form a single organ. The rods are known to be anastomosed in groups with a single conducting neuron.

† Parsons' 'Colour Vision,' Cambridge, 1915, p. 30.

height at about this point, and as might be anticipated it is in a region of *minimum* change of hue with change of wave-length. Abney's green sensation is at about $515\ \mu\mu$ its position being based on the colour vision of the green blind.

The red sensation according to Helmholtz and König lies at the very extremity of the visible spectrum, in the purplish red or a little beyond it. That is at $800\ \mu\mu$ or even greater wave-length. The blue sensation is defined by Helmholtz as an ultramarine blue. Abney takes a point in the violet beyond G. This will be, say, at $420\ \mu\mu$.

It will be found, taking Helmholtz's green as at $550\ \mu\mu$, that the frequencies at these three points may be represented by the three numbers—2 : 3 : 4. The blue and the red sensations are thus an octave apart. To this fact the blue tone of the extreme red and the red tone of the extreme blue have been before now ascribed: the octave in auditory sensations being the most perfect of the concords. The physical interpretation of this will be presently shown.*

(7) According to the present theory, the frequencies just cited as proper to the fundamental colours would bear the interpretation that the "red" quanta (*i.e.*, quanta stimulating the red sensation) act by stimulating two nerve fibres of the cone. The "green" quanta stimulate three fibres; and the "blue" quanta stimulate four fibres of the cone, or numbers of fibres proportional to these figures; although for various reasons the smaller numbers appear to be most probable.

(8) As we know, the several sensations are stimulated by a considerable range of frequencies, and, in fact, they largely over-lap. This condition necessarily arises. It is certain that every quantum of the visible spectrum is competent to activate two fibres, and may do so even if they carry energy sufficient to activate three or four fibres. On the other hand, we may not assume that those quanta which most actively stimulate a fundamental colour sensation represent the minimal stimulus which will activate the particular number of fibres involved; but rather that this number of fibres may be supplied not only by superior quanta but also by quanta from

* It is possible to find the relative values 3 : 4 : 5 in the frequencies of fundamental sensations. The end-stretches permit a choice of frequencies over lengths where there is no change of hue. Suppose, then, we take for the fundamental green sensation $505\ \mu\mu$. This gives a frequency which we represent by the number 20. The other frequencies taken as 15 and 25 give the wave-length $660\ \mu\mu$ and $400\ \mu\mu$, both of which are within the end-stretches. On these figures, however, the red and violet sensations are not an octave apart. There is evidence that they are, in fact, an octave apart; see (6). These figures, too, involve a larger minimal number of fibres. Here, again, the simpler ratios commend themselves.

neighbouring inferior points on the spectrum. The symmetrical curve of the green sensation perhaps best reveals what is happening, for in the case of the red and blue sensation curves, end conditions imposed by the failing absorption of the visual purple intrude themselves and largely define the external slope of the curves. In the case of the green curve we find a rounded crest of maximum green sensation, and in the slopes leading up to it we perceive the increasing number of quanta which go to activate three fibres and thus create in our cerebrum the green colour sensation. At the same time we see by the over-lap of the red curve that this region also pays toll to the red sensation; many quanta degrading to stimulate but two fibres.

In those cases where stimulation is attended by a misfit there may also be one-fibre stimuli. The one-fibre stimulus simply creates the luminous achromatic sensation proper to the rods.

The stimulation of the red sensation—*i.e.*, of two fibres—is displayed the whole length of the spectrum. It falls off rapidly after the demand of the three-fibre sensation begins to make itself felt, but continues right into the violet. According to Abney's measurements, the violet sensation includes 72 per cent. of red and 28 per cent. of blue sensation. Here the value of the quantum has risen to fully twice that required for a two-fibre stimulus, and in this way, possibly, excites in the cerebrum the sensation of red.

The blue colour sensation curve—according to König—gives away relatively few quanta to the green sensation curve. This may be explained, perhaps, in this way. The stimulation of four fibres leaves five vacant fibres. If a second stimulus of four fibres takes effect there is not room for a three-fibre stimulus. Now in the case of the "green" quanta spending themselves on two-fibre stimuli the element of chance is more in favour of the degradation. Two successive three-fibre stimuli leave room for a two-fibre stimulus.

(9) On the present theory the points of maximum change of hue for a given displacement along the spectrum is physically explained as follows:—Where colour sensation curves over-lap we know that quanta are being distributed among the fibres in two or three different ways. Thus, for instance, some may go to create two-fibre stimuli and some to create three-fibre stimuli. At some point on the spectrum, where the two-colour curves intersect, an equal number of quanta stimulate each sensation. Here a small change of the energy value of the quantum determines a flux of quanta to one fibre system more than to another. At this point there is a maximum rate of change of hue for a given change of wave-length.

(10) An interesting deduction from the present theory is that, under conditions of increasing stimulation with any one colour, there should be change of hue leading ultimately to white sensation. This is so because if the supply of quanta is in excess of what will engage all available fibres there will arise summation of stimuli, and finally the complete activation of all nine fibres. The sensation of being dazzled then arises, and we feel the white sensation, the more normal creation of which is due to simultaneous orderly excitation of two, three and four fibre groups.

(11) The bearing of these views on colour-blindness is as follows:— Following Dr. Parsons, I shall use the term deuteranope to denote the green-blind dichromate, and the term protoranope to denote the red-blind dichromate. To make my remarks more intelligible, I reproduce here (fig. 2) König's and Dieterici's curves.*

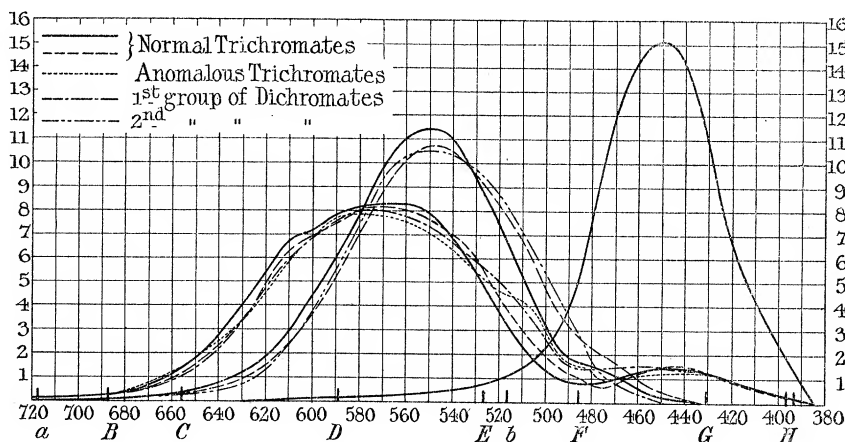


FIG. 2.

The red curve and the blue curve of the deuteranope are normal. We have therefore no reason to suppose his colour interpretive mechanism respecting red and green different from that of the normal retina. He possesses a two-fibre sensation and a four-fibre sensation. He sees his "white" light (grey) at a point on the spectrum, where at the intersection of the two curves both colours stimulate equally. He must possess six fibres leading from his cone, as compared with nine in the case of the normal eye.

It is, I think, easy to understand that this number will not favour the development of a green sensation. White light prevails above all other in Nature, for white is the colour of sun-light. His receptive mechanism, when fully activated by white light, can stimulate but two complete

* 'Die Grundempfindungen,' König and Dieterici, Hamburg and Leipzig, 1892.

sensations: the blue and the red. Hence, although it is certain that "green" quanta reach his cone, they, as such, find no sensational response in his brain. He is blind to them as stimulants of green sensation. The "green" quanta effect such stimulation of red and blue sensation as takes place in the normal eye; but there is a large residual number of them which are lost to him. The total luminosity of the spectrum is less for him than for normal vision, as is well seen in Abney's curves of photopic luminosity.

The red-blind or proteranope possesses a spectral range of colour vision identical with the green and blue of normal colour sight. The maximum height, as given in these curves, is a very little less. The blue curve is normal. Hence we conclude that he possesses three-fibre and four-fibre vision. All that has been said above respecting the eye possessing six fibres applies to the eye possessing a total of seven fibres. The loss of red vision involves a considerable deduction from the total luminosity of the spectrum, as Abney's curves show.

The scotopic or rod-vision of the dichromate is normal. It is the result of a one-fibre stimulus.

The monochromate's case is interesting. Apparently, he possesses but one fibre leading from the cone. His foveal vision is rod-vision. The normal achromatic scotopic curve and the monochromate's curve shown in König's figure are identical. It is to be recalled that this curve is also that of the light absorption of the visual purple and of its rate of bleaching. The monochromate possesses no more than twilight vision.

Cases of so-called blue-blindness are rare, and have generally been pathological in character, as is the case in subjects investigated by König. Little seems known respecting this abnormality. An eye with this defect would possess a total of five fibres, according to the theory under discussion.

(12) In the foregoing pages, and in those yet to come, the unit light stimulus discharged by a single visual fibre is frequently referred to. It represents a very small quantity of energy. Its actual amount is unknown. It must not be confused with the quantum which plays the part merely of the finger on the trigger. This minute quantity of energy discharged into the cerebral cortex evokes our unit of luminous sensation. This is a constant of deep interest to us, and one which dominates our psychology, and, indeed, our very existence as intelligent beings.

I propose to designate it a photon, using the English plural, photons. Symbolically, the letter ϕ will be assigned to it.

(13) The question naturally arises:—Are we to suppose nine fibres quite unco-ordinated in the cone, or are the fibres fused or grouped in bundles so

that we can regard them as functionally reduced to three nerves, the liminal excitatory stimuli of which are in the ratio of 2:3:4: units of energy, and which discharge into the visual centre of the brain quantities of energy in the same ratio, that is, 2:3 and 4 photons?

The latter assumption certainly facilitates the conception of their manner of functioning. If such is the real state of the case, the cone of the deuteranope possesses but two nerves or nerve-groups, having excitatory stimulus values in the proportion 2:4. His green-blindness follows at once, for he does not possess any apparatus competent to discharge an intermediate stimulus—*i.e.*, one of the value of three photons. So also in the case of the protoranope; the missing apparatus is that which discharges two photons in the cerebral cortex, *i.e.*, which creates the red sensation.

It seems, however, possible that nine unco-ordinated fibres offer an equally good explanation of the whole matter. For consider the development of colour-vision in the young child. The three fundamental sensations have never before been experienced, but they are latent, and will in due course arise as part of his consciousness. In the normal eye, white light—which is by far the most abundant and prevalent light in Nature—excites all of the three latent sensations, and in an equal degree. Later, when coloured objects attract the attention of the child, the latent sensations begin to assert themselves separately under the specific stimulus of each colour. Two-fibre stimuli excite the latent red sensation, and so on.

In the case of the green-blind there are only six fibres present. He may possess as an infant all the three sensations latent. However, the ubiquitous white light activates six fibres only. Now these must be two- and four-fibre stimuli, for, admitting that the three quanta possess an equal chance in the first instance of capturing their appropriate number of fibres, these quanta have to compete with two-fibre and four-fibre quanta, and the allocation two and four alone activates *all* the fibres, a state which is characteristic of white light and must arise under photopic conditions. His two-fibre sensation and his four-fibre sensation are, therefore, developed, while a latent three-fibre sensation will become atrophied. Three-fibre (green) quanta will, indeed, as in the normal eye, activate much red sensation and some blue sensation fibre-groups. Otherwise he fails to get any benefit from the quanta. In the case of the red-blind the same causes are operative to retard or annul the education of the red sensation. The anatomical question at issue might possibly yield to histological research.

(14) In order to understand in what manner all the varied hues of the spectrum arise out of the present hypothesis, consider a specific case, say, yellow sensation. Yellow sensation is felt when $2\phi + 3\phi$ are simultaneously

discharged at the visual centre of the brain. That is, we see it at a point on the spectrum where the quanta activate both two-fibre and three-fibre groups in about equal numbers. Somewhat nearer to the red end the quanta, owing to their lesser energy, affect the three-fibre groups in less numbers than they affect the two-fibre groups. So that there are, say, $n \times 2\phi + m \times 3\phi$ (n being greater than m) discharged in the visual centre. This excites an orange sensation. Such an expression as I have just written down is at the basis of colour sensation equations.

The hue at any point, therefore, depends on the destination of the spectral quanta radiated at that point; that is, upon their allocation among the fibre groups which they are competent to activate.

There are a considerable number of distinguishable hues, an appreciable amount of sensation being evoked by a very few quanta.

(15) The stimulus value of the three colour sensations in such proportions as to give white light is nine photons. Two colours are complementary to each other when the sum of their stimulus values is equal to 9ϕ . Thus red = 2ϕ is the complement of blue-green = $4\phi + 3\phi$. Again, green = 3ϕ is complementary of $2\phi + 4\phi$, which is a colour not found in the spectrum, *i.e.*, purple. Yellow = $2\phi + 3\phi$ is complementary of blue = 4ϕ .

(16) It is a fact that at their achromatic scotopic thresholds all lights are of equal brightness.* This is explicable on the view that rod stimulus is conveyed through a single fibre, and that a one-fibre stimulus is the minimum wherever it originates in the retina. For we are here brought into contact with the "all or none" law. It is not the quantum of energy which is transmitted: the quantum plays the part of the force applied to the trigger. What is transmitted is that unit of energy which the visual nerve generates and discharges into the cerebral cortex. The statement is an assertion of the existence of the photon.

(17) The basis of colour vision may, according to the foregoing views, be stated as follows:—

(a) The number of spectral quanta converted to electronic energy and thereby rendered capable of exciting vision is controlled by the light absorption and bleaching of the visual purple (or substance possessing a similar spectral absorption curve).

(b) The quanta, increasing in energy from the long to the short wavelengths, stimulate two, three and four fibres of the cone according to their energy, as shown by the colour sensation curves.

(c) The simultaneous stimulation of two fibres is attended by the red

* Parsons, *loc. cit.*, p. 61.

sensation; of three fibres by the green sensation; of four fibres by the blue sensation.

(d) The unit of luminous stimulus is the nerve discharge of one fibre.

(e) No colour sensation is associated with this stimulus.

(18) It seems difficult to question any of these statements if there is any reality in the present theory. But the long-standing question respecting colour sensation confronts us: Can we deal with these cerebral phenomena quantitatively; in a physical sense? It is a question most difficult to answer. Possibly it is ultimately unanswerable. I think, however, the present theory gives a little to go on.

It seems probable that the numbers of photons characteristic of each of the fundamental colour sensations constitute an energy relation between them. The colour sensation curves depict the amount of excitation of three cerebral effects in answer to spectral stimuli. Each sensation is an accompaniment of a particular form of energy stimulus, *i.e.*, of two, of three, or of four photons simultaneously discharged. To the *form* of the stimulus the specific character of the sensation is to be referred. We must be prepared to admit that an energy equivalent to the sensation must exist. *Ex nihilo nihil fit.*

If we measure the maximum heights attained by the three colour sensation curves of König* (or the two colour sensation curves in the case of dichromates) we find them related to the frequencies of the corresponding primary colours; that is the heights are, for the red, green, and blue curves, in the ratios 2:3:4 approximately. Thus we find for the maximum ordinates (green and blue sensations) of the proteranope the heights 10·8:15·2, *i.e.*, a ratio of 3:4 approximately, and for the deuteranopes red and blue maxima 8:15·2, *i.e.*, a ratio of 2:4 approximately. In the trichomate the three colour sensations attain the stimuli values 8·2:11·4:15·2, which are in the ratio of 2:3:4 approximately.

This seems to suggest that the quantitative values of the three sensations stand in the ratio of the number of photons originating each sensation. Herein is an energy relation between the colour sensations, if I have viewed the matter rightly.

(19) Luminosity or brightness would seem to be a sensation directly dependent on the number of electrons which stimulate the nerve fibres. This appears to be a necessary inference from the fact that curves of spectral luminosity in general and the curves of absorption and bleaching of the visual purple are in fair agreement.†

We must specially notice the resemblance between the photopic and

* *Ante*, fig. 2.

† Parsons, *loc. cit.*, p. 55; compare figs. 1, 10, 11, 14, etc.

scotopic luminosity curves.* Now the latter according to the present theory, can represent but one photon from each electron. We must conclude that the former also represents one photon from each electron.

(20) From this we must infer, as regards photopic luminosity, that the number of fibres activated by one electron does not influence the luminosity stimulus. The stimulus remains a unit stimulus, irrespective of whether it originates from two, three, or four grouped fibres.

If the stimulus value were proportional to the number of constituent photons, the form of the resultant photopic spectral curve must differ radically from that of the scotopic curve. It would rise towards the violet end. This feature it certainly does not exhibit. Of course, the photopic luminosity curve stands at a higher energy level than the scotopic curve. This is because the numbers of quanta acting per second are greater in the former than in the latter case.

(21) On the other hand, with respect to the excitation of colour sensation, the number of constituent photons entering into the stimulus is all important. For it is by this number, *i.e.*, by the *form* of the stimulus, that the fundamental colour sensations are evoked.

The relation of luminosity to colour sensation is, therefore, according to the present theory, as follows:—Luminosity is the more primitive sensation, and at first was associated entirely with rod vision. The evolution of the cone brought in multiple stimuli, and the sensation evoked became correspondingly complex. The basal luminous sensation remained, excited as before by a nerve stimulus from the retina, but it was accompanied now by a new and additional sensation, that of colour.

Colour sensation necessarily involves luminous sensation. It necessarily involves it because the energy is there which excites it. The converse proposition is not, however, true. It is not true, because there may be sufficient energy to excite a luminous sensation and not sufficient to excite colour sensation. The separation of colour sensation from luminous sensation is therefore impossible. Colour sensation curves take both into account.† Hence the energy relations revealed in the relative heights of the three curves, as referred to above, is to be expected.

It is easy to see that there is a balance of energy available for the colour stimulus. The unit of luminosity is referable to the photon. Red sensation is seen when two photons act simultaneously. We may ascribe one to the luminous and one to the colour sensation. As both arise together, and are, in fact, superimposed, this allocation of the energy is perhaps a little fanciful.

* Parsons, *loc. cit.*, fig. 14.

† König and Dieterici, *loc. cit.*, p. 22.

However, it must possess a basis of fact, for it affords an explanation of the relative luminosities of the colour sensations. For red, the energies are equally divided; for green, two go to the colour sensation and one to the luminous; for blue, the allocation is three and one. Hence the last is the least luminous of the colour sensations.

(22) Another matter finds explanation in these considerations. The colourless interval between the general threshold and the colour threshold is for long wave-lengths (beyond $670 \mu\mu$) almost completely absent. "In fact, even with very good dark adaptation, such a red light excites the sensation of red."* The small energy values requisite to excite both colour and luminous sensations in the case of red sensation explains this observation. Very feeble electrons served to excite both. With less luminous colours it is otherwise. In these cases, a relatively small number of the electrons liberated from the sensitiser carry into the cone the requisite energy to build up the stimulus to the value of the colour sensation. For the blue sensation, the colourless interval is therefore the greatest.

(23) On these views white is a sensation arising in the loss of form attending the activation of all nine fibres. This loss of form causes it to resemble the luminous sensation. It is neither a true luminous nor yet a true colour sensation, but something sharing the properties of both. It is a nine-fibre sensation, *sui generis*.

(24) One of the most remarkable facts of vision is its marvellous range: from the feeblest twilight to full mid-day sunshine. In photopic vision a very large number of electronic stimuli probably do not and cannot take effect, even if we assume a very brief refractory period. The figures are instructive.

I assume at least nine nerve fibres, discharging stimuli, in each cone, and that the normal refractory period is 10^{-4} sec. A total of 9×10^4 stimuli can be accepted per second per cone. If we estimate the number of cones in the fovea as 2×10^4 , this area might transmit 18×10^8 stimuli. The number of electrons or quanta involved is one-third of this where white light is concerned; or, say, 6×10^8 quanta per second.

A standard candle gives $5 = 10^5$ ergs per second (Rayleigh), and from this 4 ergs per second reach 1 sq. cm. at a distance of 1 m. Assume a ten-candle-power light, and that the pupil has closed down to the area of 3 sq. mm. Further, suppose the image of the source of light just covers the fovea. Under these conditions 0.22 ergs reach the fovea in one second.

Now the value of a "green" quantum is about 5×10^{-12} erg. Hence the energy reaching the fovea will give rise to about 4×10^{10} quanta or electrons

* Parsons, *loc. cit.*, p. 61.

per second, or about seventy times the possible transmission. Of course there would be some loss by absorption in the media of the eye, and, again we may not limit the refractory interval as we have done. It might be ten times smaller and yet not fall below the value apparently associated with audition. But even so, we must recognise that in photopic vision the flash of the electron may often come at the wrong moment and fail to evoke vision.

An important deduction from this consideration is that a highly dilute visual purple may suffice for the requirements of photopic vision. The fact that dark adaptation of the fovea is feeble supports this view.

The Effect of Red Fatigue on the White Equation.

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The white equation, that is the amount of pure spectral red, green, and violet, required to match a simple white, is of fundamental theoretical importance. The apparatus used in these experiments is of similar principle to that of Abney, namely, the selection of portions of the spectrum by slits and their re-combination on a white surface by means of a lens, but with several improvements suggested by Captain Fulton. The source of light is a "Pointolite" lamp of 1000 c.p. The light is focussed on the slit of a collimator, from which it emerges in a parallel beam. It is then dispersed by a compound prism of the Amici type. A lens placed close to the prism focusses the spectrum on the slits, the light being reflected by a mirror placed in the path. A second lens is constructed so as to take the whole spectrum, portions of which are isolated by means of slits. The focal length of the lens is arranged so that an image of the last surface of the prism is projected on a screen, the colour being dependent on the portion or portions of the spectrum isolated by the slits. In order to obtain a long light-path, the light is again reflected by a second mirror before reaching the screen. The intensity of a comparison patch of white light is regulated by an adjustable diaphragm placed in the path of light. The apparatus is used in a dark room free from stray light.

The three lights used in these experiments were a red of λ 6670– λ 6770 Å., a green of λ 5144– λ 5156 Å., and a violet of λ 4250– λ 4267 Å. In making the equation, the red and violet slits are kept unaltered, the equation being made by closing or opening the slit, allowing green light to pass. The size